SITE RESPONSE OF ORGANIC SOILS IN THE DELTA

by

R. W. Boulanger, Rajendram Arulnathan, and I. M. Idriss
Department of Civil and Environmental Engineering, University of California, Davis, CA 95616

USGS Award No.:	1434-HQ-96-GR-02747
Award Recipient:	University of California
Principal Investigators:	Ross W. Boulanger & I. M. Idriss
Title of Application:	Site response of organic deposits in the Delta
Program Element:	II
Objective Number:	Panel NC

Research supported by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 1434-HQ-96-GR-0247, and the Department of Water Resources, State of California. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government or the State of California.

Final Technical Report

Center for Geotechnical Modeling
Department of Civil & Environmental Engineering
University of California
Davis, California

April 1999

USGS Award No. 1434-HQ-96-GR-02747

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R. W. Boulanger
Department of Civil and Environmental Engineering, University of California, Davis, CA 95616
ph: (530) 752-2947, fax: (530) 752-7872, email: rwboulanger@ucdavis.edu

Rajendram Arulnathan
Department of Civil and Environmental Engineering, University of California, Davis, CA 95616
ph: (530) 752-0586, fax: (530) 752-7872, email: rsarulnathan@ucdavis.edu

I. M. Idriss
Department of Civil and Environmental Engineering, University of California, Davis, CA 95616
ph: (530) 752-0586, fax: (530) 752-7872

TECHNICAL ABSTRACT

Seismic stability of the Sacramento-San Joaquin Delta levee system is a major concern for the State of California. A primary source of uncertainty in any evaluation of the seismic stability of the Delta levee system is the amplification/attenuation response characteristics of the shallow organic soils that commonly underlay the levees. This report summarizes research on the site response characteristics of organic soils using centrifuge and numerical modeling. The centrifuge modeling effort included the development of techniques to measure the shear wave velocity profile for a centrifuge model while in-flight. Excellent agreement was obtained between shear wave velocities measured in the centrifuge tests and in laboratory triaxial tests using piezo-ceramic bender element methods. Centrifuge model tests included variations in the soil profile, the earthquake waveform, and the level of earthquake shaking. One-dimensional site response analyses using an equivalent linear procedure were performed with the measured shear wave velocity profiles and the modulus reduction and damping relationships determined from prior laboratory studies. Good agreement was obtained between the numerical simulations and the centrifuge model recordings. The experimental results provide improved confidence in our ability to model site response characteristics of organic soil deposits.

ACKNOWLEDGEMENTS

Support for this research was provided by the U.S. Geological Survey (USGS), Department of the Interior, under USGS award number 1434-HQ-96-GR-02747, and the Department of Water Resources (DWR), State of California. The National Science Foundation contributed to the development of the in-flight measurement system for shear wave velocity under the PI's Career Award, CMS-9502530. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government or the State of California.

The system for measuring shear wave velocity in the centrifuge was developed in collaboration with Bruce L. Kutter, along with technical support from Bill Sluis, Tom Kohnke, and Dan Wilson, of the University of California at Davis. The research described herein is part of a continuing collaborative effort with Leslie F. Harder, Jr., Raphael A. Torres, and Michael W. Driller of the DWR on the dynamic response of organic soils. All of the above support and assistance is greatly appreciated.

1. INTRODUCTION

The seismic stability of the Sacramento-San Joaquin Delta levee system is a major concern for the State of California. Inundation of any of the major islands due to levee failure during a period of low outflow could draw saline water from San Francisco Bay into the Delta, impeding water exports. The State of California Department of Water Resources (DWR 1992) performed a preliminary evaluation of the seismic stability of the levees and concluded that the greatest source of uncertainty was the "amplification/attenuation characteristics of shallow organic soils" which commonly underlay the Delta levees. Their assessment of site response characteristics was hampered by the lack of data regarding the dynamic properties of organic soils (including peat).

Levees in the Delta are highly heterogeneous due to a combination of geologic and historical factors. Geologically, channel migration and stream meandering have resulted in heterogeneous underlying strata. Historically, construction of levees, beginning with Chinese laborers and later with dredges, proceeded without select materials or the use of compaction. Levee heights have become progressively greater as Delta islands have subsided, with current heights of up to 8-m above interior island surfaces. A schematic of subsurface conditions under levees at Sherman Island is shown in Figure 1, and CPT and shear wave velocity data at one location on Sherman Island are shown in Figure 2.

The potential consequences of future earthquakes include deformations within the organic strata and/or liquefaction of the sands and silts within and beneath the levees. In fact, the static stability and deformations of levees at Sherman Island have required considerable attention and ongoing corrective actions, as reported by Foott et al. (1992). Clearly, any assessment of levee stability during earthquakes will be strongly influenced by the potential site effects.

Limited data exists regarding the dynamic properties of organic soils subjected to strong seismic shaking. Seed and Idriss (1970) presented properties for Union Bay peat in their study of recorded motions at Union Bay, Seattle, during a magnitude 4.5 earthquake. These early relationships were based on a broad interpolation of data and considerable judgment. Although their use is no longer recommended, these relationships have been widely referenced. More recently, Stokoe et al. (1994) presented test results for two peat specimens from a bridge site in New York, and Kramer (1996) presented results for tube samples of peat from Mercer Slough in Washington.

Boulanger et al. (1998) presented cyclic laboratory test results for tube specimens of peaty organic soil from Sherman Island in the Delta, with the resulting modulus reduction and damping curves summarized in Figures 3 and 4.

Determining the amplification/attenuation characteristics of shallow organic deposits will require considerable future research since so little has been done to date. Long-term needs include additional measurements of dynamic properties of organic soils in the laboratory, obtaining strong motion records of earthquake shaking at fully characterized sites, and site response analyses comparing predicted and recorded motions to assess the predictive capabilities

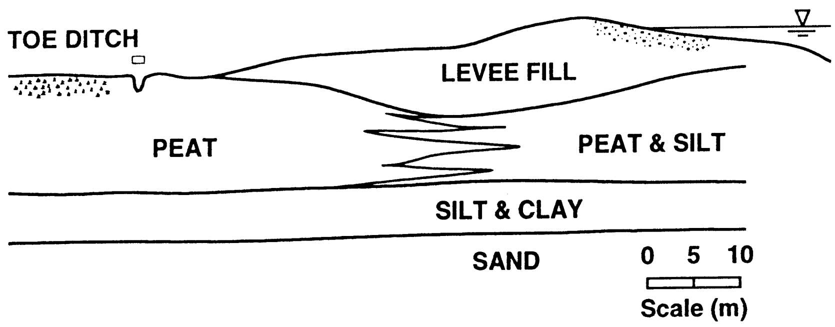

Fig. 1. Schematic of Typical Sherman Island Levee (Boulanger et al. 1998)

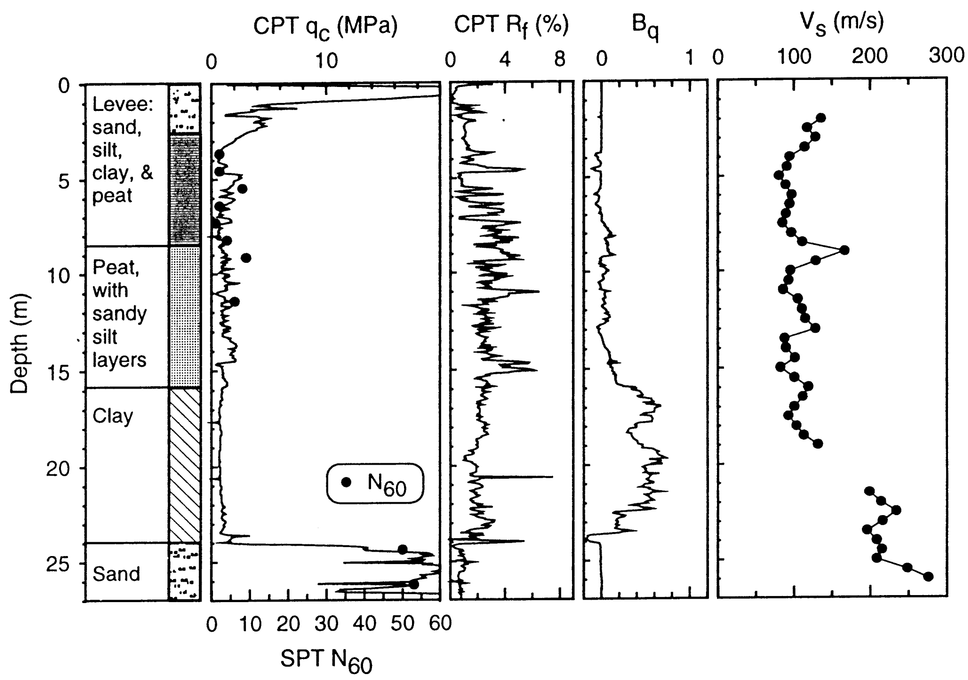

Fig. 2. SPT, CPT and Shear Wave Velocity Data at Sherman Island (Boulanger et al. 1998)

of analysis methods. In beginning to address these needs, the DWR has installed down-hole seismograph arrays at four levee sites underlain by organic soil layers of varying thickness. Obtaining strong motion records at the fully instrumented sites, however, is dependent upon waiting for the next seismic event to strike the area.

Centrifuge modeling provides a means of immediately measuring the site response characteristics of organic soils. An advantage of centrifuge modeling is the ability to do a physical parameter study, and thus observe the effects of parameters such as strata thickness, earthquake frequency content, and level of shaking. The results of experimental parameter

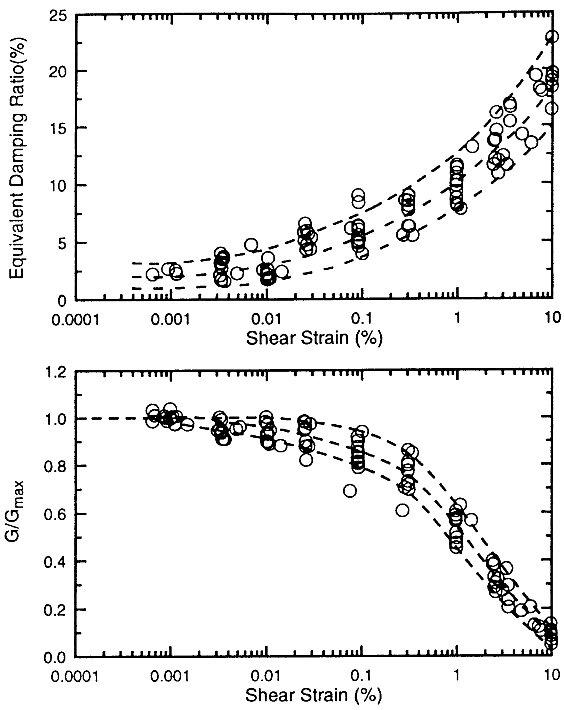

Fig. 3. Upper-range, Median, and Lower-range Curves of Modulus Reduction and Damping Ratio for Sherman Island Peat (Boulanger et al. 1998).

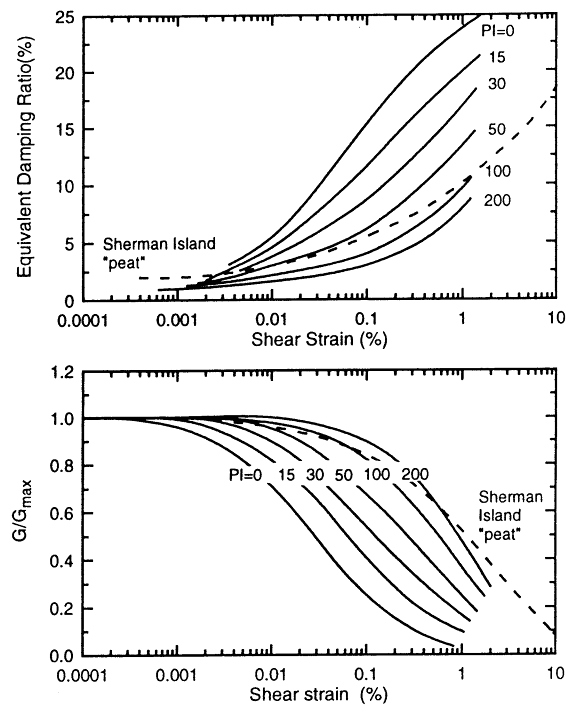

Fig. 4. Median Modulus Reduction and Damping for Sherman Island Peat Versus Curves Recommended by Vucetic and Dobry (1991) for NC and OC Clays of Varying Plasticity (Boulanger et al. 1998).

studies are useful in evaluating the ability of a numerical site response analysis method to capture the parameters' influences.

Fiegel (1995) demonstrated the application of centrifuge modeling to site response problems by measuring the response of soft clay deposits subjected to a wide range of earthquake loading conditions. The results showed, for example, that the peak surface acceleration measured in the centrifuge was amplified at low peak base accelerations and attenuated at high peak base accelerations. Also, for a given level of peak base acceleration, higher amplification ratios were recorded for earthquakes with lower frequency content (i.e., greater distance from source and higher magnitude). The centrifuge test results are in good agreement with the general trends predicted by Idriss (1991), and lead to an improved confidence in the proposed curves at strong levels of shaking where data is lacking.

The research described in this report included (1) subjecting horizontally layered profiles containing organic soil to simulated seismic loading using the 1-m radius Schaevitz geotechnical centrifuge, and (2) dynamic response analyses of the experimental profiles using the dynamic properties generated from ongoing research at UC Davis. In addition, a method for measuring the shear wave velocity profile of the centrifuge models while in-flight was developed and tested extensively as part of this study. Typical results from this research project are summarized in this report, while a more detailed description and summary of results will be presented by Arulnathan (1999).

It is believed that the results of this research have contributed to the goals of the NEHRP by developing and evaluating dynamic response models that can be used to assess variations in ground motions and potential seismic hazards throughout the Sacramento-San Joaquin Delta. Furthermore, this research was performed in cooperation with the State of California Department of Water Resources and that will facilitate the use of these findings in future evaluations of the seismic hazards in the Delta.

2. CENTRIFUGE MODELING

2.1 Facilities

Centrifuge model tests were performed using the servo-hydraulic shaker (Chang 1990) on the Schaevitz centrifuge at UC Davis. This centrifuge has a radius of about 1 m and can provide centrifugal accelerations of up to 100 g. A flexible shear beam (FSB) container was used to simulate shear beam boundary conditions for the soil. The inside dimensions of the FSB container are 50-cm long, by 23-cm wide, by 18-cm deep. Results are presented in prototype units unless otherwise noted.

2.2 In-Flight Measurements of Shear Wave Velocity

Shear wave velocity (V_s) measurements are routinely performed in the field to determine the low strain shear modulus (G_{max}) using the following formula:

$$G_{\max} = \rho V_S^2$$

where ρ is the density of the soil. V_s measurements in centrifuge models, however, have only been reported by Gohl and Finn (1987), Kita et al. (1992), and King et al. (1996). In all three cases, these investigators used piezo-ceramic bender elements to generate the shear waves.

V_s measurements in dynamic centrifuge models greatly enhance the value of the centrifuge test data for evaluating dynamic behavior and analysis methods. This is because the V_s data provide an important characterization of the models, and thus a realistic constraint on the numerical models that will eventually be evaluated against the data. For this reason, considerable effort was directed towards developing the capability to measure V_s in the centrifuge models that were performed as part of this study.

A shear air hammer was developed as the in-flight wave source. The shear air hammer consists of a hollow aluminum cylinder capped at both ends, and fitted with an air port on each end. The cylinder is about 5 cm long, and its outer surface is roughened and epoxy-coated with sand. A teflon piston, about 2.5 cm long, fits inside the cylinder. Tubing connects the air ports to a four-way valve that enables the simultaneous application of air pressure to one end of the cylinder while venting the other end. The four-way valve is operated by a solenoid that provides

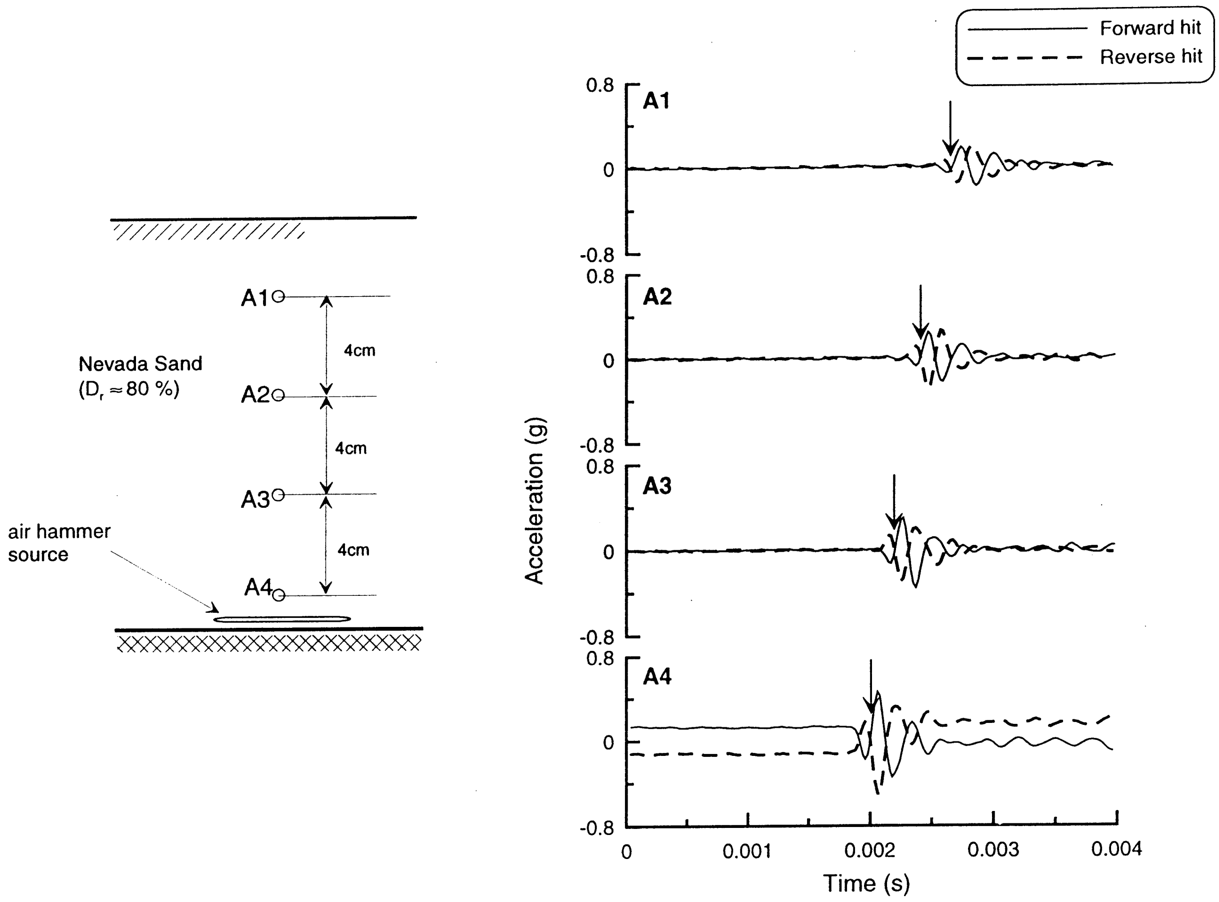

Fig. 5. In-flight Shear Wave Travel Time Records on Nevada Sand ($D_r \approx 80\%$) from Centrifuge test using Air Hammer Source at 80 g.

fast opening and closing actions. When the four-way valve is opened in one direction, the piston is fired towards the end of the cylinder by the applied air pressure. When the four-way valve is opened in the opposite direction, the piston is fired towards the opposite end of the cylinder.

The shear air hammer is embedded horizontally in the soil profile of a centrifuge model during placement of the soil. In the tests reported herein, the shear air hammer was placed roughly in the middle of the container, just above the base. Four accelerometers were placed in an array directly above the shear air hammer.

After the model has been spun up to the desired centrifugal acceleration, the shear air hammer can be triggered to fire in either direction. The impact of the piston with an end of the cylinder produces a system of waves that emanate from the outer surface of the cylinder. Tests described later suggest that the desired effect of shear waves emanating from along the outer circumference of the cylinder was reasonably achieved. A four-channel digital oscilloscope is used to capture the signals at the four accelerometers above the shear air hammer. The shear air hammer is then triggered in the opposite direction and another set of signals are recorded.

A typical set of signals and the experimental set-up are shown in Figure 5. The soil profile in this case was a uniform deposit of dry dense Nevada sand. These signals were obtained at a centrifugal acceleration of 80 g. The signals are of good quality, and the "forward" and "reverse" signals clearly assist in identifying the characteristic points of the wave pattern.

The quality of the signals shown in Figure 5 represents considerable iteration on the shear wave source. These iterations included trying solenoid hammers on the base of the container, but that was found to produce significantly more complicated wave patterns in the soil due to wave reflections in the container itself. With regard to the shear air hammer eventually selected for use, the final design reflects trials with a variety of piston materials and sizes, cylinder sizes and lengths, and air source pressures and plumbing details.

The reasonableness of the in-flight V_s measurements was checked against piezo-ceramic bender tests in a triaxial device. An example of the signals obtained in bender element test is shown in Figure 6. These results were obtained from a tube sample of Sherman Island peat as part of an earlier study (Boulanger et al. 1998). The interpretation of bender element tests, and the main sources of error are discussed in Arulnathan et al. (1998).

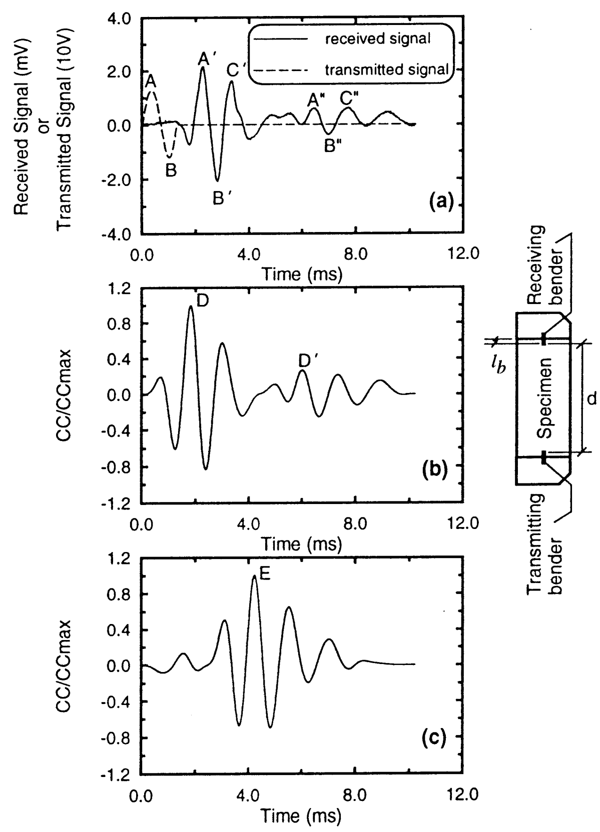

Fig. 6. Example of Bender Element Test Results to Measure Shear Wave Velocity in a Cyclic Triaxial Specimen: (a) Transmitted and Received Signals; (b) Cross-correlation of Transmitted and Received Signals; and (c) Cross-correlation of First and Second Arrivals in Received Signal. (Boulanger et al. 1998).

The first check tests were performed on dense, dry Nevada sand at a relative density of about 80%. Centrifuge V_s data was obtained over three depth intervals on the same model at progressively increasing g-levels of 10, 20, 40, and 80 g. This procedure provided V_s data over a wide range of confining stresses on a single soil profile. The data obtained from two such tests are summarized in Figure 7(a). V_s measurements were also obtained on triaxial specimens of the same sand using piezo-ceramic bender element tests. The triaxial specimens were anisotropically K_o-consolidated with the imposed K_o value being 0.44 (i.e., $K_c=\sigma_{1c}'/\sigma_{3c}'=2.27$). V_s data was obtained for each specimen at progressively increasing values of confining stress. The data from two such specimens are summarized in Figure 7(b). Equations relating V_s to the mean confining stress were obtained by linear regression for the bender element test data (Fig. 7(a)) and the centrifuge test data (Fig. 7(b)). Regression on either set of data produced a stress exponent of 0.25, which is the value expected for clean sand. Furthermore, the V_s values obtained in the centrifuge and the triaxial device were essentially identical over the entire range of imposed confining stresses, as illustrated by the essentially identical regression results.

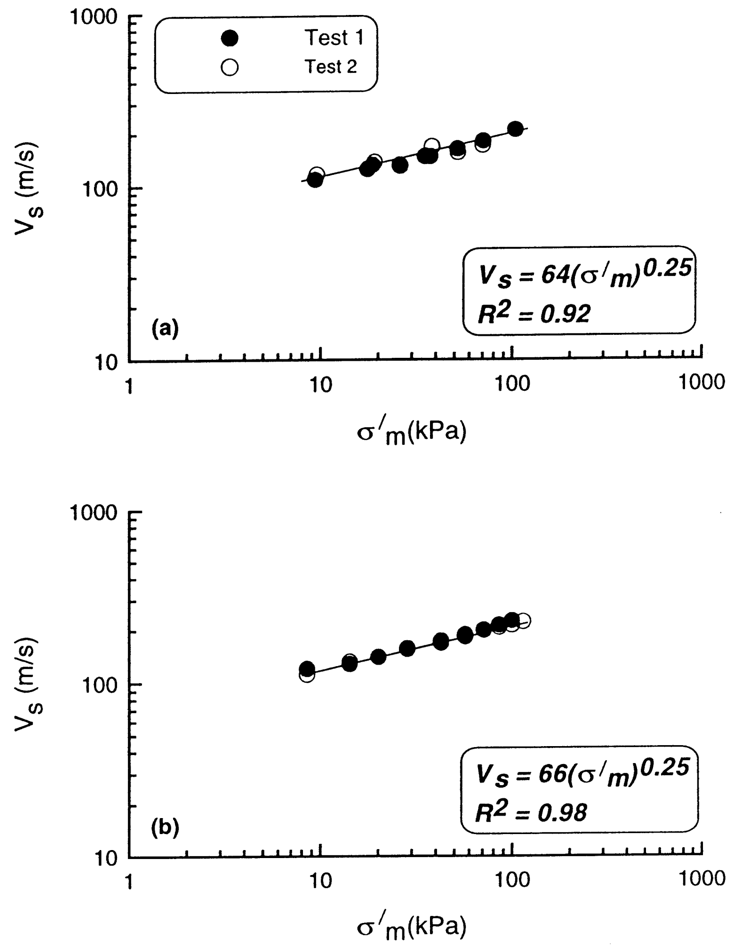

Fig. 7. Summary of Results from Tests 1 & 2 on Nevada Sand ($D_r \approx 80$ %). (a)Centrifuge Tests (b) Bender Element Tests

A similar comparison of in-flight V_s measurements with bender element measurements was also performed on a reconstituted peaty organic soil ("peat"). V_s data in the peat was only obtained at a single g-level because of the long time required for in-flight consolidation. V_s values were generally obtained over two depth intervals in the peat in each of two centrifuge tests. Piezo-ceramic bender element tests were performed over a wider range of consolidation stresses in a triaxial device, and at different ages and anisotropic stress ratios. The resulting V_s

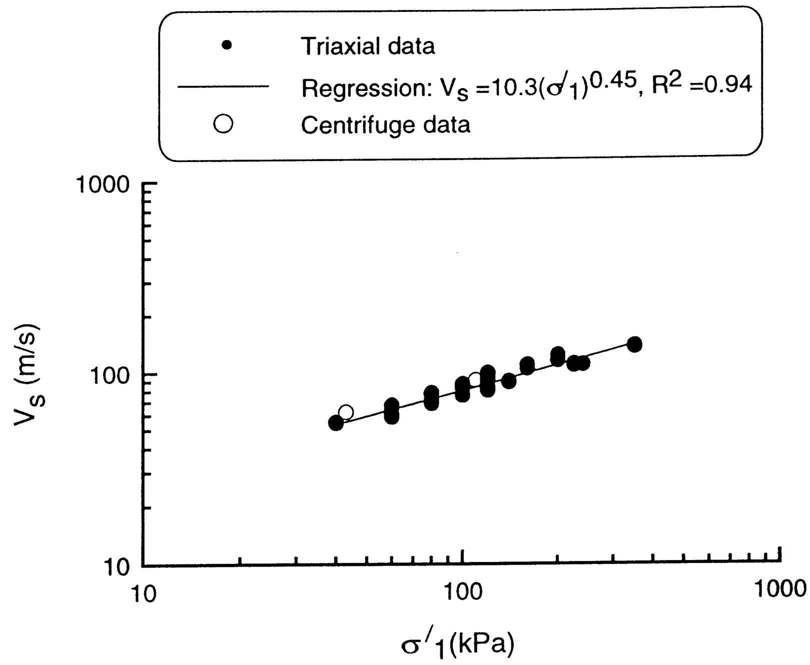

Fig. 8. Summary of Bender Element Tests on Reconstituted Sherman Island Peat (after 5 days of consolidation)

data are compared in Figure 8, and show that the in-flight V_s measurements are in excellent agreement with the laboratory test values.

2.3 Dynamic Centrifuge Models With Organic Soil Layers

Soil models were prepared that consisted of an upper dense sand layer, a middle peat layer, and a lower dense sand layer. The thickness of each layer was varied to control the range of consolidation stresses on the peat and the fundamental period of the entire soil profile. The soil profile used in one of the dynamic centrifuge tests is shown in Figure 9.

The sand layers were constructed by dry pluviation to a relative density of about 80%. The sand was placed dense to avoid liquefaction during shaking. Liquefaction of the sand was undesirable because the focus of these tests was on the peat behavior, and the effects of liquefaction on site response would have complicated subsequent interpretation. After the lower sand layer was placed, it was subjected to a vacuum, flushed with carbon dioxide, and then saturated with water. The peat was prepared for placing as follows. First a large supply of peat tube samples from Sherman Island were acquired. These samples had ash contents of 35 to 56%, and maximum fiber lengths of about 1 to 2 cm. Samples were conditioned with extra water to bring their water contents up to about 340%, and then allowed to soften for one day. The samples were then easily dissected by hand so that the fibers were fully separated, rather than torn. All the peat samples were then mixed together in one batch and subsequently separated into uniform portions for testing. The resulting peat "slurry" was then placed in lifts in the centrifuge container, and then mechanically consolidated under a vertical stress equal to the effective vertical stress that would later be applied during the centrifuge test. After consolidation, the peat

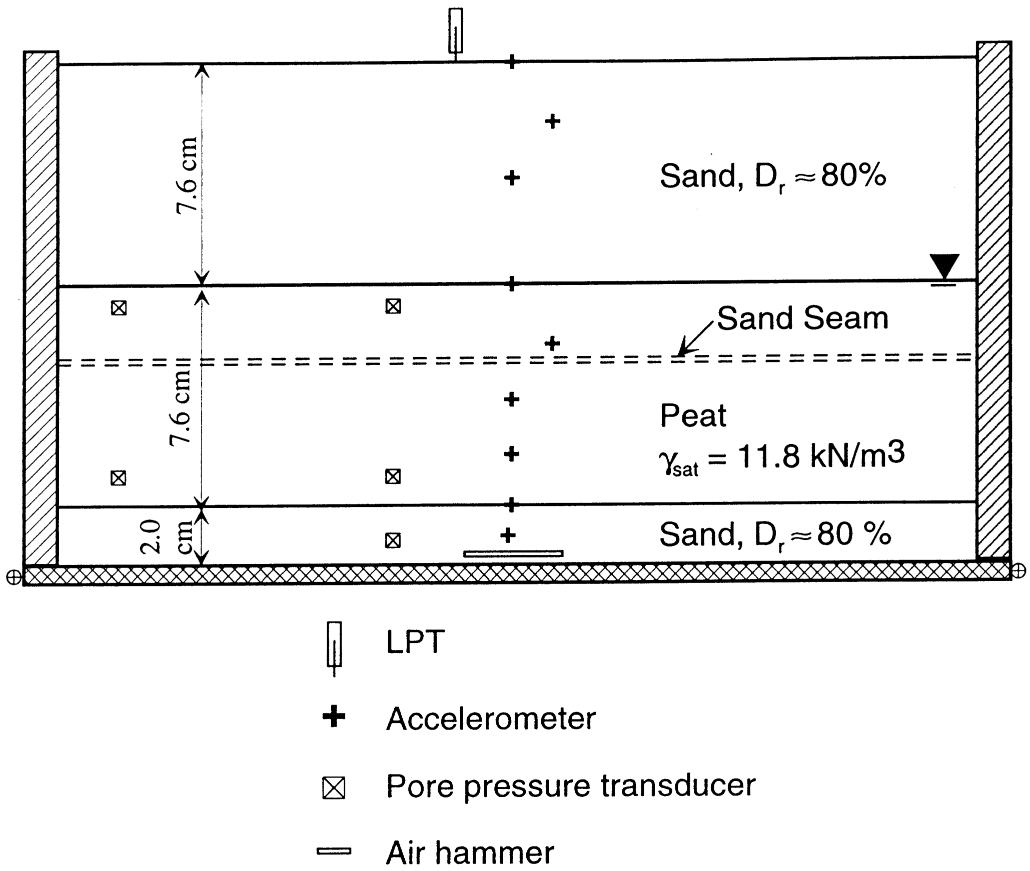

Fig. 9. Configuration of Centrifuge Model 2 in a Flexible Shear Beam Container

layers had water contents of about 140%. Finally, the upper sand layer was placed by dry pluviation to a relative density of about 80%.

Instrumentation included accelerometers, pore pressure transducers, and a displacement transducer to measure vertical settlements. The instrumentation arrangement for one of the tests is shown in Figure 9.

The models were spun to the desired g-level and allowed to fully consolidate, as evidenced by the pore pressure and settlement readings. Each model was then subjected to a series of earthquakes, progressing from small shaking events to large shaking events. Any excess pore pressures generated by the shaking were allowed to fully dissipate before the next shaking event. V_s measurements were taken before the first shaking event, after select shaking events in the series, and after completion of the last shaking event. These data allowed an evaluation of how the cumulative effects of several shaking events affected the V_s profile.

Pore pressure dissipation rates were very slow in these models, indicating that the peat layers acted perfectly undrained during earthquake shaking in these tests. This is similar to the observations made during centrifuge model tests with clays, and indicates there is no concern over the inconsistent scaling of consolidation and dynamic processes. That is, when a centrifuge test is performed at "n" times gravity and time is scaled for "dynamics" (i.e., divided by "n"), then the model drains "n" times faster than the prototype would if water is the pore fluid in both the model and prototype. In our models, the "n" time faster consolidation is still in the perfectly "undrained" range of behavior, and thus has no effect on model behavior.

The organic fibers in these models were generally less than 1 cm in length, and at most 2 cm in length. These fiber dimensions are small relative to the container dimensions, and thus it is believed that any effects of scaling will be generally small compared to the other effects of concern in centrifuge modeling (rate effects, boundary conditions, aging).

The potential effects of soil-container-shaker interaction were evaluated by placing sets of accelerometers at the same depth but at different plan locations in the model and on the container rings to obtain a measure of motion coherency at any one depth. Preliminary interpretations of the data indicate that soil-container interaction effects were reasonably small. These results are still being compared to data on soil-container interaction by other investigators at UC Davis.

3. TYPICAL COMPARISON OF CALCULATED AND RECORDED RESPONSES

3.1 Analysis Method

A large amount of data was obtained from the centrifuge model studies, and these data are currently being analyzed and interpreted by Arulnathan as part of his doctoral research. The analyses include back-calculation of stress-strain behavior for the peat, and 1-D site response analyses using the available information for dynamic properties of peat. Typical results from the site response analyses are presented in this report, while further detail will be presented by Arulnathan (1999).

Site response analyses were performed for each shaking event using the equivalent linear site response program, SHAKE91 (Schnabel et al. 1972, Idriss and Sun 1991). The in-flight V_s measurements were used to define the low-strain shear moduli (G_{max}) input to the analyses. The modulus reduction and damping relationships selected for the peat layer were the median relationships obtained for tube samples of Sherman Island peat by Boulanger et al. (1998), as shown in Figures 3 and 4. The modulus reduction and damping relationships for the sand layer were selected based on relationships commonly used in practice. The results presented herein used the relationships recommended by Seed and Idriss (1971).

3.2 Typical Comparisons

Calculated and recorded site responses for an earthquake motion with a peak base acceleration of 0.1 g are compared in Figures 10 to 12. Acceleration time histories are shown in Figure 10 for 10 different depths in the soil profile, with recorded motions shown on the left (Figure 10a) and calculated motions on the right (Figure 10b). The corresponding acceleration response spectra (ARS) for the same 10 depths are shown in Figure 11. Maximum accelerations and maximum shear strains are plotted versus depth in Figure 12.

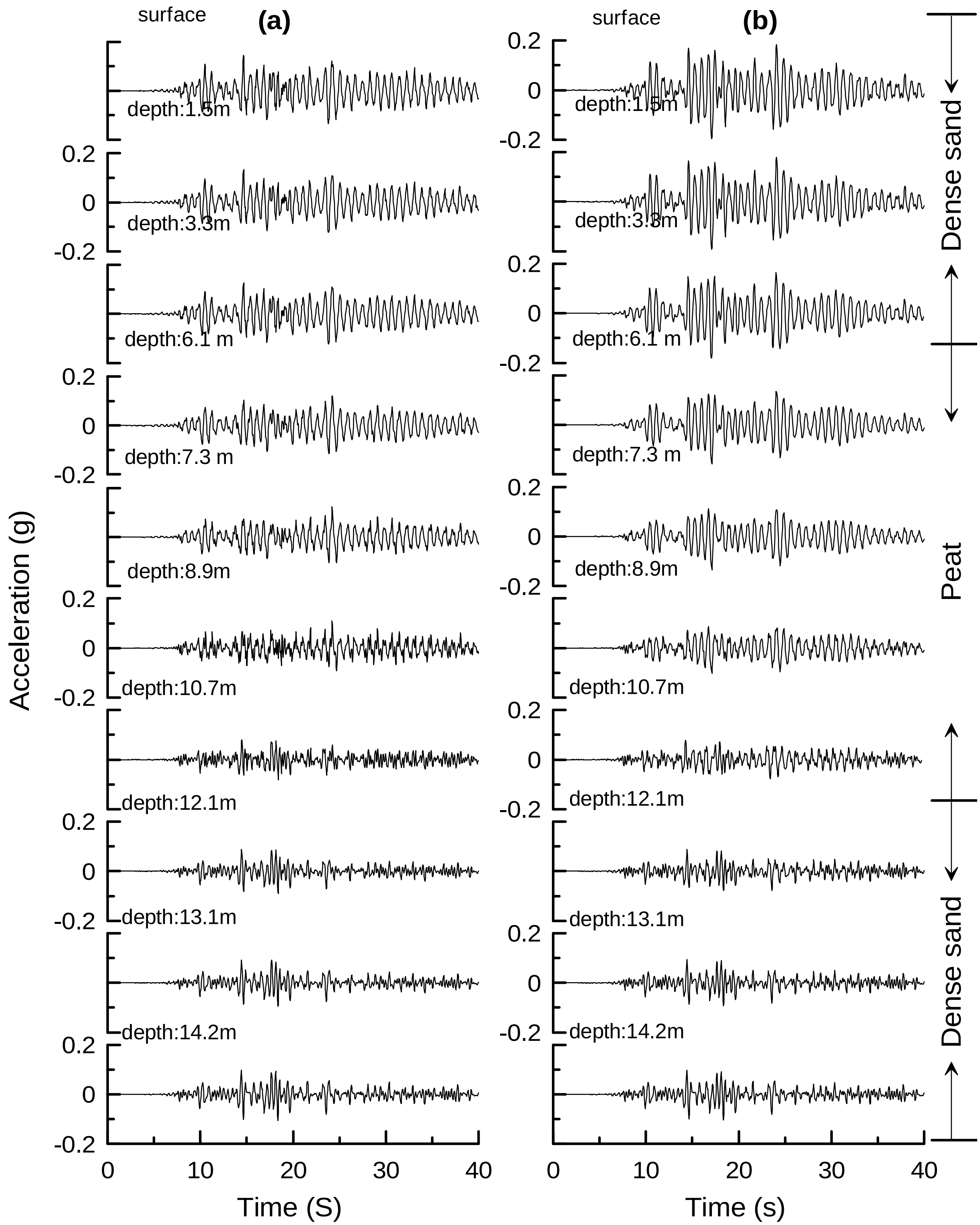

Fig. 10. Acceleration Time Histories at Ten Depths for Model 2 During an Earthquake with Peak Base Acceleration of 0.1 g.: (a) Recorded (b) Calculated

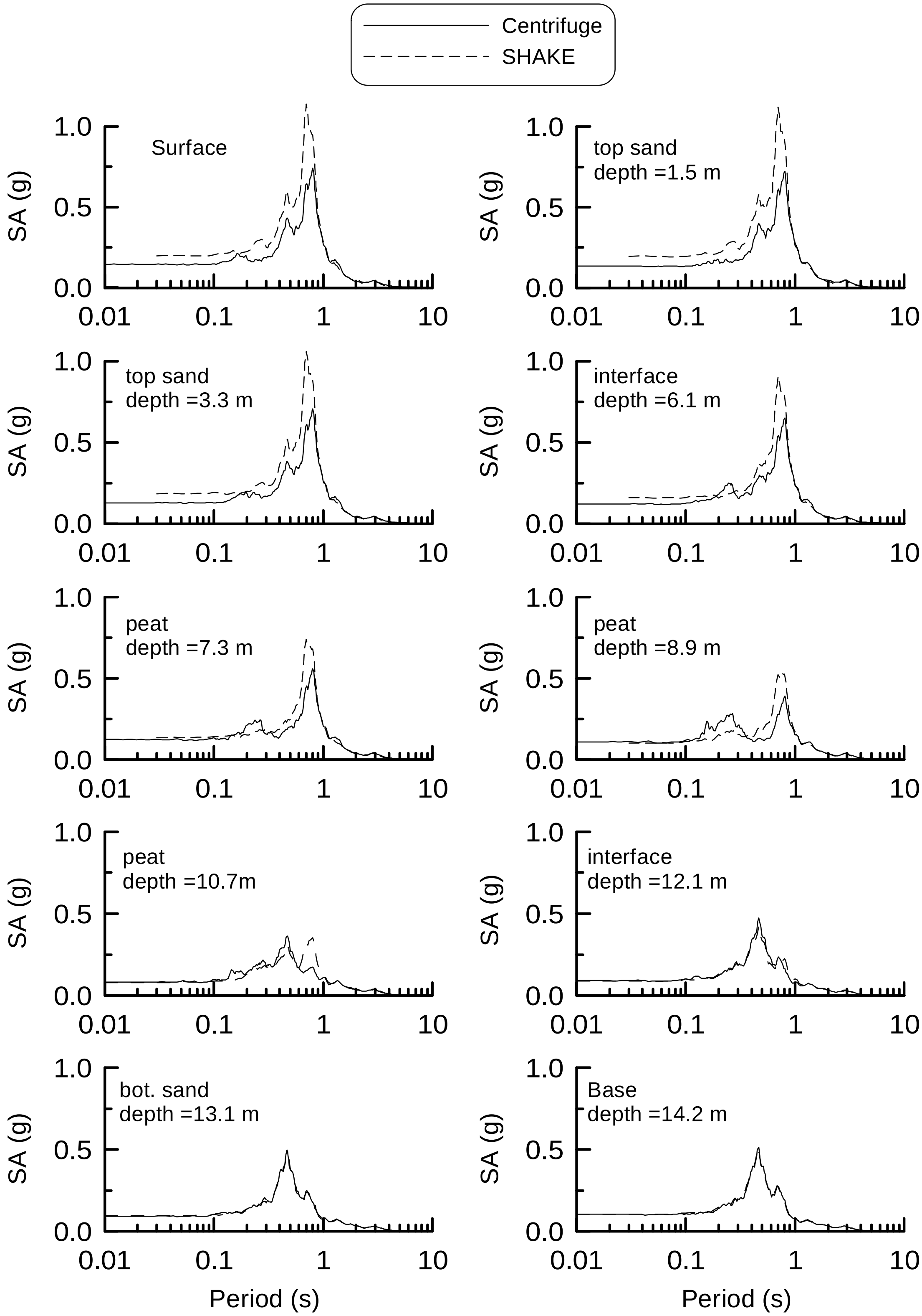

Fig. 11. Acceleration Response Spectrum (5% damping) for Ten Depths in Model 2 During an Earthquake with Peak Base Acceleration of 0.1 g.

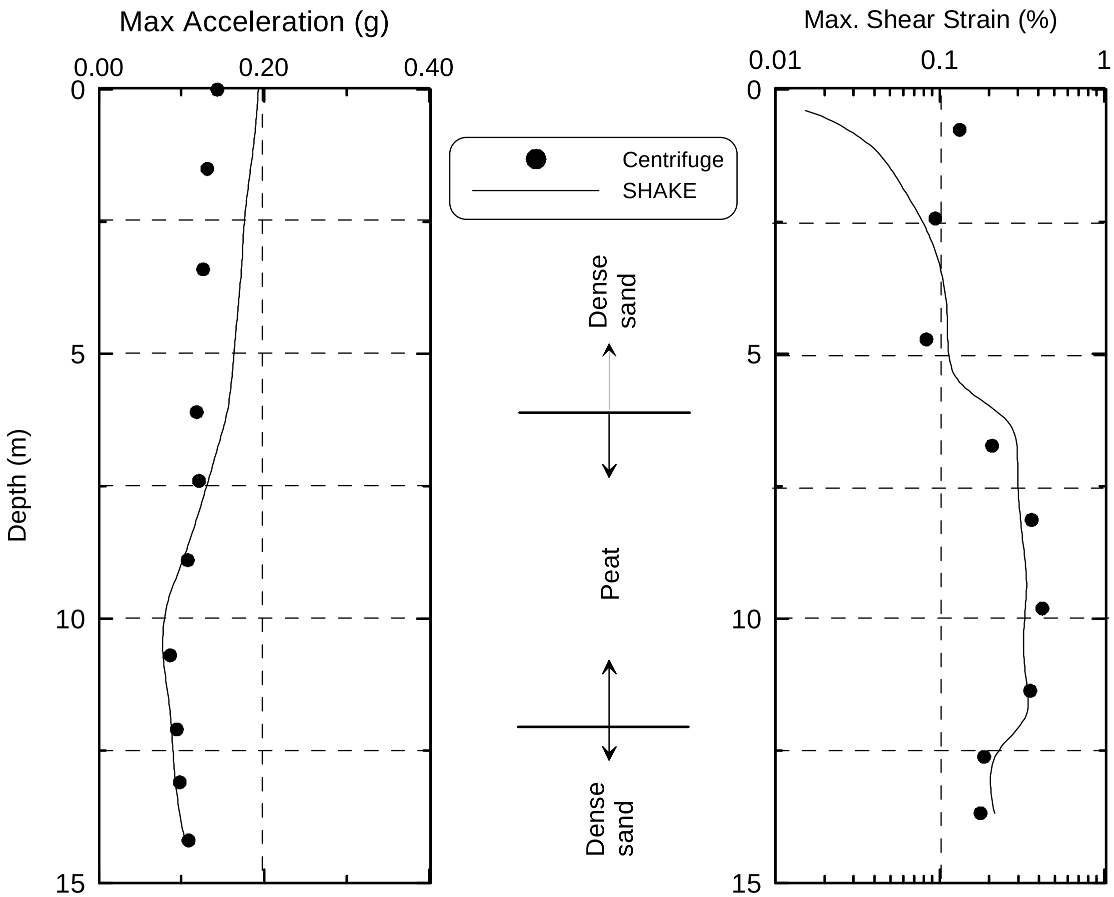

Fig. 12. Peak Acceleration and Shear Strain Variation with Depth for Model 2 During an Earthquake with Peak Base Acceleration of 0.1 g.

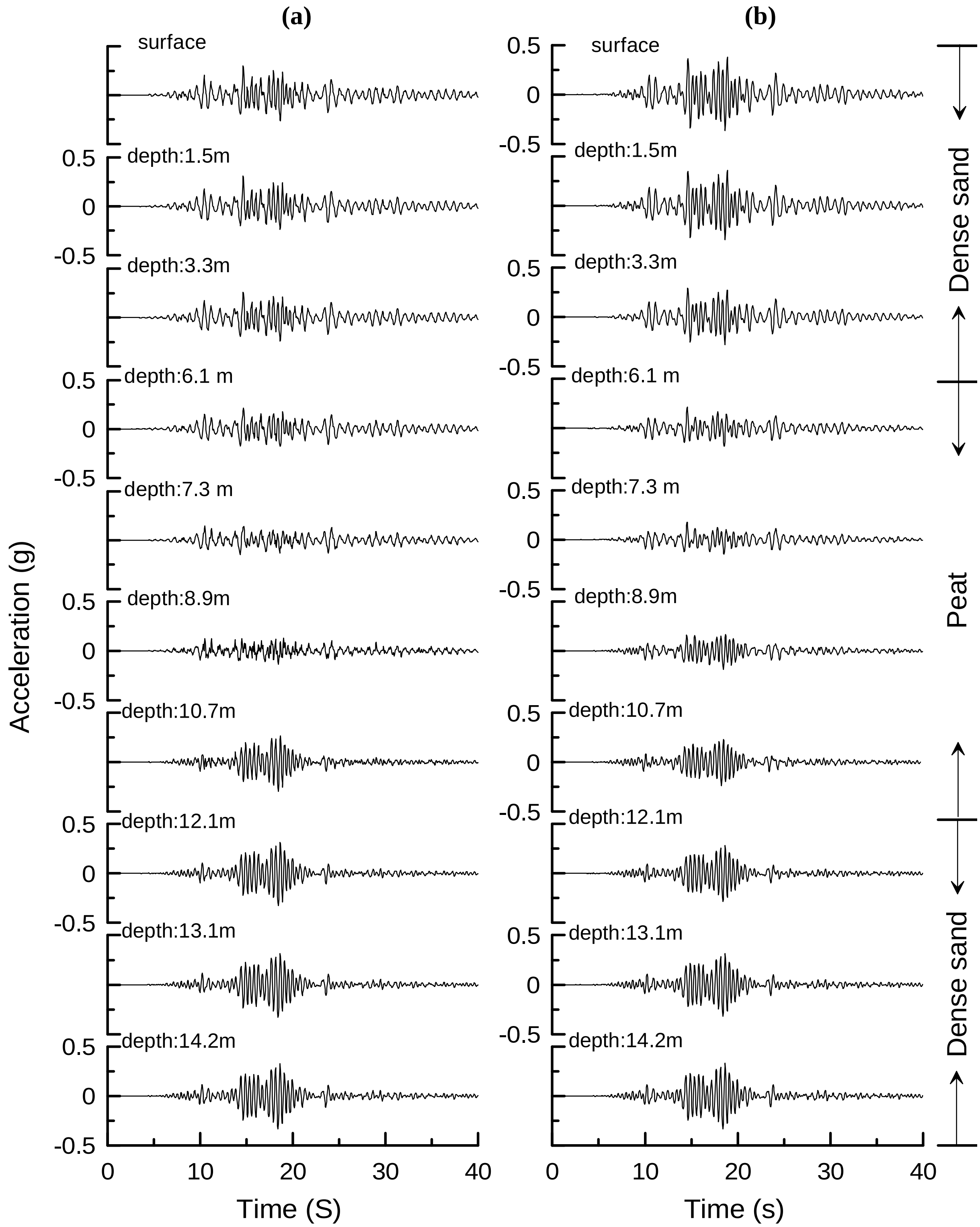

Fig. 13. Acceleration Time Histories at Ten Depths for Model 2 During an Earthquake with Peak Base Acceleration of 0.33 g.: (a) Recorded (b) Calculated

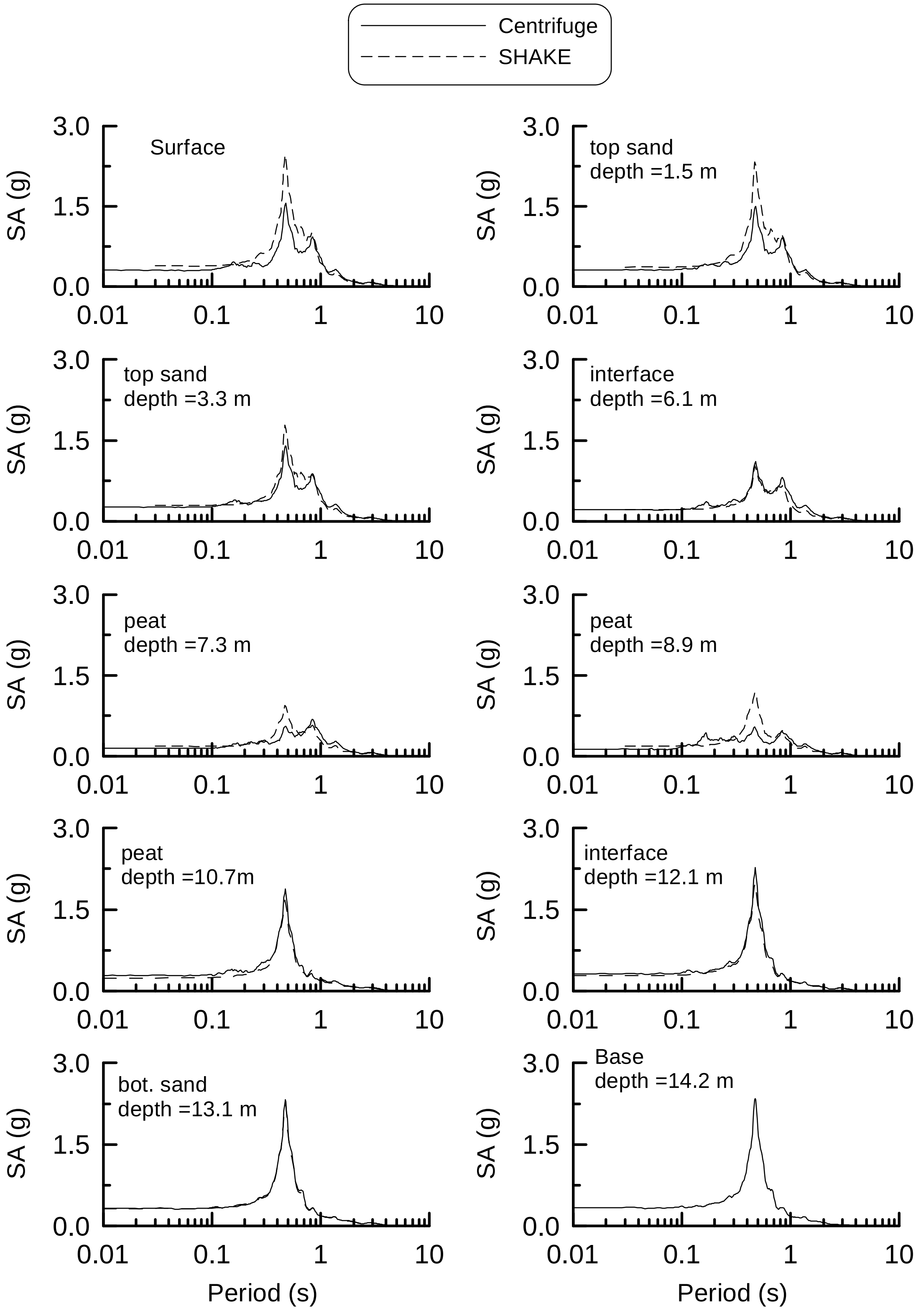

Fig. 14. Acceleration Response Spectrum (5% damping) for Ten Depths in Model 2 During an Earthquake with Peak Base Acceleration of 0.33 g.

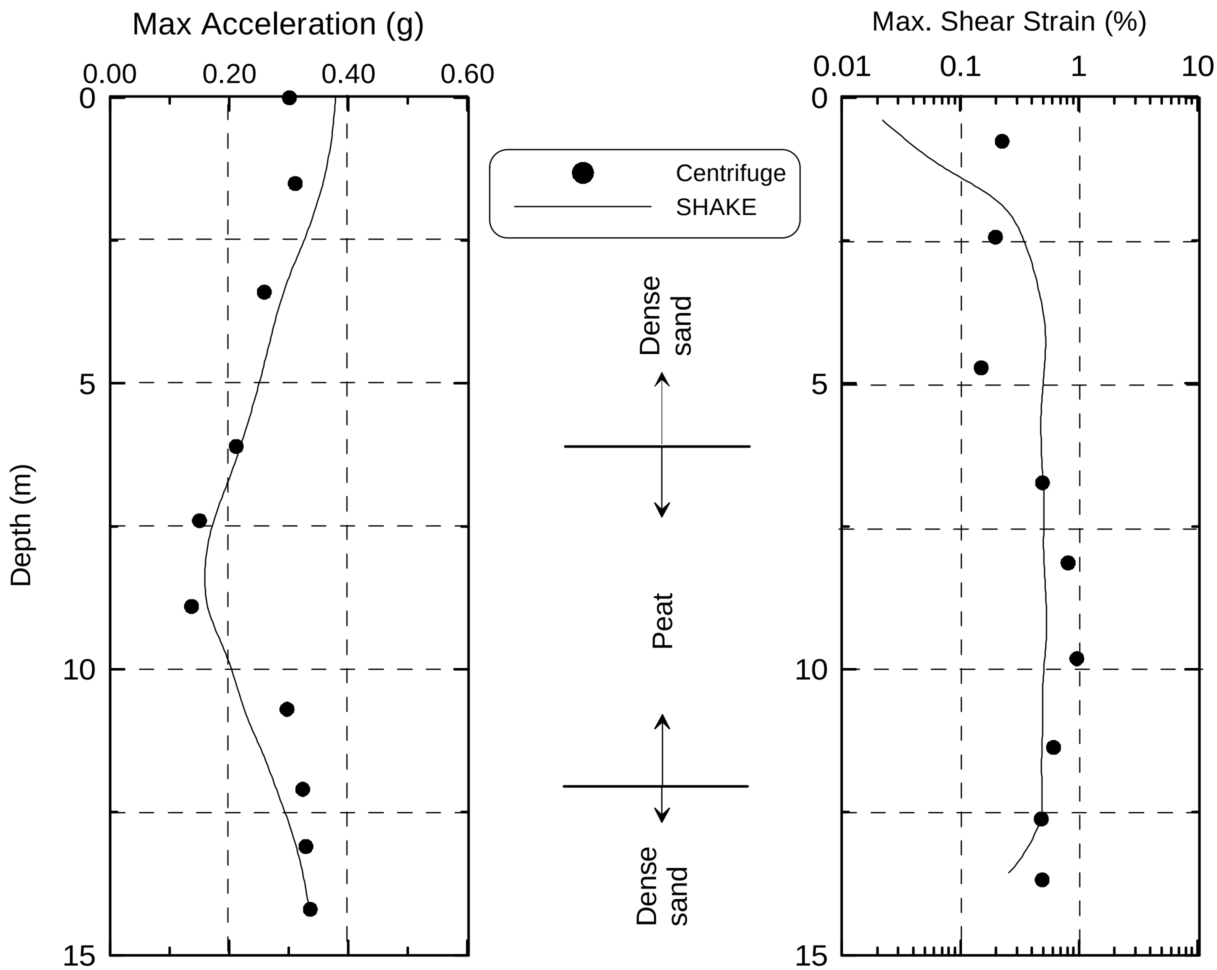

Fig. 15. Peak Acceleration and Shear Strain Variation with Depth for Model 2 During an Earthquake with Peak Base Acceleration of 0.33 g.

A similar set of calculated and recorded site responses for an earthquake motion with a peak base acceleration of 0.33 g are compared in Figures 13 to 14. Acceleration time histories and ARS are compared for the same 10 depths in Figures 13 and 14, and maximum accelerations and maximum strains are compared versus depth in Figure 15.

The calculated and recorded responses are in good agreement for both of these typical earthquake events. In the smaller earthquake event, the analysis overestimated peak accelerations and underestimated peak shear strains in the upper sand layer. The agreement in the larger earthquake was slightly better, but there was also a slight overestimation of peak accelerations and peak shear strains in the upper portions of the upper sand layer. These observations only pertain to these two earthquakes, however. More general conclusions must wait until analyses and comparisons can be completed for all the earthquake events and models tested in this study, which all together total 38 cases to analyze.

These typical centrifuge and analysis results illustrate the type of experimental data that was recorded, the general features of the soil profile responses, and the ability of the 1-D site response model to reasonably reproduce the centrifuge responses for these two earthquakes. As noted previously, more detailed analyses and interpretations of these data will be presented in Arulnathan (1999).

4. SUMMARY

This report provides an overview of research performed during this study on the site response characteristics of organic soils using centrifuge and numerical modeling. Detailed results and final conclusions will be presented by Arulnathan (1999).

Techniques for measuring the shear wave velocity profile of a centrifuge model while in-flight were developed. Extensive check tests were performed to determine if shear wave velocity measurements in the centrifuge tests were in agreement with measurements in laboratory triaxial tests using piezo-ceramic bender element methods. Excellent agreement was obtained for dense sand over a wide range of confining stresses, and for reconstituted peat over the range of confining stresses used in the model tests. The development of in-flight shear wave velocity measurements greatly improved the value of the dynamic centrifuge tests performed later in this study.

Dynamic centrifuge model tests were performed for soil profiles consisting of a peat layer with overlying and underlying sand layers. The models were designed to produce confining stresses in the peat layer that are representative of stress conditions under levees in the Sacramento-San Joaquin Delta. The dynamic centrifuge model tests included variations in the soil profile, the earthquake waveform, and the level of earthquake shaking. One-dimensional site response analyses using an equivalent linear procedure were performed with the measured shear wave velocity profiles and the modulus reduction and damping relationships determined from prior laboratory studies. Typical results were presented for two different earthquakes with peak base accelerations of 0.10 and 0.33 g, respectively. Good agreement was obtained between the numerical simulations and the centrifuge model recordings. Further analysis results and interpretations will be presented in the doctoral thesis of Arulnathan (1999).

The experimental results and analyses are expected to provide improved confidence in our ability to model site response characteristics of organic soil deposits.

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